(NASA-TM-79271) NEUTRALIZATION TESTS ON THE SERT 2 SPACECRAFT (NASA) 24 p HC A02/MF A01 CSCL 22B

N79-33255

Unclas

G3/20 45837

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Prepared for the
Fourteenth International Conference on Electric Propulsion
sponsored by the American Institute of Aeronautics and Astronautics
and Deutsche Gesselschaft fur Luft- und Raumfahrt
Princeton, New Jersey, October 31-November 2, 1979

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E-191

Abstract

Orbit precession returned the SERT II spacecraft to continuous sunlight in January 1979 for the first time since early 1972, and new experiments were planned and conducted. Neutralization of an ion beam was accomplished by a second neutralizer cathode located 1 meter away. Plasma potential measurements were made of the plasma surrounding the ion beam and connecting the beam to the second neutralizer. When the density of the connecting plasma was increased by turning on the main discharge of a neighboring ion thruster, the neutralization of the ion beam occurred with improved (lower) coupling voltage. These and other tests reported should aid in the future design of spacecraft using electric thruster systems. Data taken indicate that cross neutralization of ion thrusters in a multiple thruster array should occur readily.

Introduction

The Space Electric Rocket Test II (SERT II) spacecraft was launched in 1970 with a primary objective of demonstrating long-term operation of a space electric thruster system.[2] Progress towards that objective was completed late in 1970 when each of two ion thruster systems on board developed a high-voltage grid short. The continuing functional state of the spacecraft has permitted an expansion of the original scope of mission to include demonstration of ion thruster system space storage and restartability,[2] and the study plasma efflux between two thruster systems (subject of this paper). These added tests are possible since the spacecraft returned to a continuous sunlight orbit on January 11, 1979 and continuous power is available to perform testing.

The study of plasma surrounding an electric thruster propelled spacecraft is of interest in the design and control of the neutralizer system of each thruster system and of the combined group of multiple thrusters. SERT I spacecraft test in 1964 proved that broad ion beam neutralization occurred in space without problem. Neither SERT I nor early SERT II tests studied or attempted to model the interaction of the ion beam, neutralizer, and local and ambient plasma electron flux. Understanding such interactions should aid in the control of multiple thruster neutralizers and may lead to improvements in the design of neutralizers.

This paper presents neutralization test data obtained during the first 3 months of 1979. Tests include ion beam neutralization of a thruster by a close (normal design) neutralizer as well as by a distant (1 meter away) neutralizer. Parameters affecting neutralization, such as neutralizer bias voltage, neutralizer anode voltage, local spacecraft plasma density, and solar array voltage configuration were varied and changes in plasma potentials were measured. A preliminary plasma model is presented as an approximation of observed results. Much of the data is presented in a matrix of tables and figures to permit later development of improved models based on new or other assumptions.

Continuous sunlight was lost in April 1979, but will return in August 1979 and be continuous till late in 1989. Thus future testing will be feasible.

Nomenclature

I	current, mA
n_i	ion plasma density, ions/cm^3
Neut	neutralizer
Main	main discharge of thruster
S/A	solar array
S/C	spacecraft
Supply 4	main discharge
Supply 5	screen (beam) current (i.e.; 2-I5 is beam current of T/S-2)
Supply 6	accel grid
Supply 7	neut keeper
Supply 9	neut bias
T/S-1	thruster system 1
T/S-2	thruster system 2
V	voltage, v
V_S	space plasma potential (assumed = zero v)

Apparatus and Procedure

The SERT II spacecraft is shown in Fig. 1. It consists of an Agena stage rocket with a 1.5-kW solar array on one end and two experimental ion thruster systems on the opposite end. A thruster system contains an ion thruster together with Hg-loaded propellant tanks mounted on gimbals. A thruster power conditioning and control box is located inside the spacecraft body. Each thruster system has a hot-wire probe that can be swept through the ion exhaust beam and measure its plasma potential profile. The following sections describe this hardware and operating conditions in detail.

Thruster Systems

The steady-state SERT II thruster operation at various times since 1970 is summarized in the companioned paper.[2] The information below gives normal thruster operation applicable to the data of this paper. The two thruster systems were identical in electrical and mechanical design.

T/S-1. - Data were attained with this thruster completely off, with the neutralizer discharge only lit, and with both the main and neutralizer discharges lit. Figure 2 shows a schematic wiring diagram of thruster power supplies and solar array. When on, the neutralizer discharge (V8) operated at 28±1 v and 160±10 mA. The main discharge (V4) when on, was operated at 37±1 v and 2.1±0.1 amp. The

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AIAA Paper No. 79-2064.

screen (I-V5) to accel grid (I-V6) short developed in 1970 remains, and prevented these supplies from turning on without current overload. The telemetry current return to S/C ground, however, remains functional when the supplies are off. The I5 current reads electron return to S/C ground or ions leaving the thruster. If a net flow of electrons should leave the thruster, the I5 current would read zero. The I6 current reads electrons flowing from S/C ground to the accel grid due to ion impingement. If a net flow of electrons should strike the accel grid, the I6 current would read zero. With the V6 supply turned off, the impedance to electrons flowing from S/C ground through the supply causes the accel grid to become 1.4 v positive for 0.1 mA current and 20 v, positive for 6 mA.

T/S-2. - For the tests described herein, the beam current of thruster 2 was maintained at 85±3 mA by closed-loop control. The screen voltage was 3000 v and the accel grid was -1850 v. The main discharge was 39±1 v at 1.8±1 amp and the neutralizer keeper was 28±1 v at 160±10 mA.

There was flow control interaction between the closed-loop Hg-flow control of neutralizer 2 and that of neutralizer 1. This interaction resulted in each neutralizer vaporizer heater slowly cycling (at times full on to full off every 30 sec). The change in each neutralizer keeper anode voltage, however, was only ±1 v. Occasionally, the neutralizer keeper swing would increase to as much as ±4 v. The cycling, however, was not sufficiently great to cause extinction of the neutralizer discharge.

V9 bias supply. - The V9 supply was designed to place a bias voltage between the neutralizer cathode and S/C ground. In addition to zero voltage, there are four nominal bias voltages: ±25 v and ±50 v. The common of the bias supply is connected to S/C ground and the output then drives the neutralizer cathode either (+) or (-) with respect to the S/C frame. The bias voltages were generated by flowing current across a zener diode stack with voltage magnitude and polarity changes made by a command switching network. Current to produce negative bias was produced internally within the supply, but neutralizer emission current was required to produce positive bias. At times, when there was little or no neutralizer emission, the nomimal positive V9 voltage did not appear on the neutralizer. The reader is cautioned to look at the actual I-V9 and 2-V9 values listed in data tables instead of the nominal bias command values. The I9 telemetry read emitted electron current from S/C ground through the neutralizer cathode to space plasma. If electron flow was in the opposite direction, I9 telemetry would read zero.

Hot-Wire Probes

The SERT II spacecraft was designed with three hot-wire emissive probes to measure plasma potentials.(4) One probe, which burned out in 1971, was at the end of a 1.5-meter long beam protruding ahead of the S/C body. The other two probes were each at the end of an arm that rotated it into and out of each ion beam. The two beam probes are shown in Fig. 3. Beam probe 1 was jammed and remained stationary in a position fully away from the beam center, but was electrically operative. The probe voltages listed in table 1 are data as received from the S/C and are relative to S/C frame. All plasma potentials shown on figures are relative to space plasma potential which is assumed zero.

Beam probe 2 functioned normally. When commanded, it began rotating and was heated at the same time. The telemetry system sampled the probe potential reading every 4 seconds. Fifty seconds were required to make one sweep. Possible probe reading positions are shown in Fig. 4. As the "probe-on" command and telemetry sampling times were not synchronized, the positions of readings are not always those shown in Fig. 4. One sampling, however, must always occur in the ion beam. Micro switches stop, reverse sweep direction, and turn off the probe at each end of travel, leaving an arc of 60° not traversed by the probe 2 sweep.

Beam probe 1 readings could be obtained continuously and recorded by an on-board tape recorder. Several times this was done and data over a full orbit were obtained, both with and without a thruster operating. Beam probe 2, however, completed a sweep in 50 seconds and turned off automatically. Therefore, data from beam probe 2 could only be in real time while passing over a ground tracking station. Useful pass time over any one station was limited to about 15 minutes or less. This led to the following test procedure: T/S-2 was operated at a fixed bias on the neutralizer (1-V9 constant) for the entire pass; T/S-1 neutralizer bias (1-V9) was set alternately to 0 v, ±25 v, and ±50 v bias with a 50-second sweep of beam probe 2 at each bias level. With the command time required to change bias between probes sweeps, approximately five to eight sweeps could be completed per pass. A set of sweeps was called a "test" and is so listed in table 1.

Typical sweep data showing each data point are shown in Fig. 5. Subsequently presented beam profiles omit most data points for clarity. Each line of table 1, however, lists probe data points for the beam center, beam edge, and end of probe travel. Average values for beam probe 1 and thruster operation is also listed together with the S/A voltage and S/C longitude and latitude. Usually, a pass starts with a sweep at zero bias and repeats a sweep every 90 to 120 seconds thereafter. The sequence of sweeps may be determined by the longitude value which normally decreases with time. A pass number, listed for each test number of table 1, aids to identify the test number with spacecraft control room tape records.

Solar Array

Description and 1979 performance curves for the SERT II main solar array (S/A) are presented in Ref. 2. The 1430-W (beginning of life, BOL) array was degraded to about 63% of BOL maximum power and this power limit prevented cross neutralization operation at ion beam currents greater than 85 mA. In general, for these tests, the negative side of the S/A was connected to S/C ground. For several tests, however, the S/A was switched to a center-tap configuration which was the normal configuration in Ref. 4. Both of these wiring configurations are shown in Fig. 1. S/A operating voltages are listed in table 1 and the small voltage variation is due to load change.

Spacecraft

The complete spacecraft in orbit, shown in Fig. 1, consisted of two basic cylindrical structures plus a solar array. One structure was 1.1 m

long and 1.5 m in diameter. It housed all experiments and accessory instrumentation. This structure was directly attached to the empty Agena rocket. The empty Agena consisted of a cylindrical section 4.6 m long and 1.5 m in diameter, plus a 1.5 m section containing the rocket nozzle and solar array. These factors result in an area for ram ion current collection of 10.4 m^2 which was the nominal frontal area of the spacecraft.(4)

In 1979 the spacecraft was spin stabilized about an axis perpendicular to the plane of the S/A. For the time during which the data of this paper were obtained, the spin rate was about 5 rpm and the angle of the spin axis to the orbit normal was about 15°. This angle exposed the S/A to ram current and increased the nominal frontal area by 1 m^2. The exact S/C attitude changed slowly within a period of several weeks. If more precise values are desired, the reader is invited to contact the authors at the Lewis Research Center, Cleveland, Ohio.

A variety of surface coatings resulted from thermal control considerations, i.e., paint, polished Al, and Al tape. All paints used were of a nonconductive type. All unpainted metal surfaces on the main cylindrical section were electrically connected to a common spacecraft ground. The thermal control pattern resulting allowed the possibility of small potential gradients across the spacecraft surface. Reference 4 indicates that the calculated positive area exposed for electron collection (with the S/A center-tapped) was 1.1 m^2. Due to the S/C spinning, the frontal ram area cycled from the maximum 10.4 m^2 to a value about one-half of that. In addition, the 15° angle of the spin axis to the orbit normal resulted in a small exposed ram area for the S/A. This area changed as the sine of the orbit revolution angle, resulting in S/A front side exposure to ram current for half an orbit and backside exposure for the other half orbit.

Telemetry Data Accuracy

All S/C data is in the form of 0 to 63 counts, but each parameter has its own scale factor. The list below give the value of 1 count change in each parameter. The uncertainty is ±0.5 count. Some of the values in table 1 fall between counts due to a time averaging of the data. There is also uncertainty in the data of table 1 due to the updating sequence of the telemetry. For example, I5 and I6 update every 30 seconds, but I9 and V9 update only once per minute. The probe voltages update every 4 seconds.

Spacecraft Telemetry Values

Parameter	1-Count value
I5	5 mA
I6	0.05 mA
I9	7 mA
V9	2 v
Probe voltage	2.4 v
S/A	1.5 v

Results and Discussion

Beam Potential Measurements

Figure 5 is a plot of thruster 2 beam plasma potentials measured by probe 2 sweeping through the beam. T/S-1 was completely off and the three curves shown are for zero, and ±50 v bias to neut 2. Each probe data point is shown to illustrate typical probe results. The probe position for each point can be related to the S/C geometry with the help of Fig. 4. Data for probe sweeps at ±25 v bias were omitted for clarity, but results of these sweeps may be found in table 1 for test 1.

The data of Fig. 5 agree well with those taken 5 years earlier:(5) the S/C potential was controlled by bias of the thruster neutralizer; negative S/C potentials were easily achieved; and positive S/C potentials were limited because neutralizer emitted electrons traveled to nearby S/C surfaces rather than escaped to the space plasma. The geometric profile of the beam plasma corresponded to the nominal thruster diameter of 15 cm with a 15° half angle maximum beam divergence angle. The maximum beam plasma potential was shifted with neutralizer bias, but not to the full magnitude change of the bias. The voltage drop between the neutralizer cathode and beam center was nearly constant at about 38 v for positive and zero bias, but increased 6 and 14 v for -25 and -50 v bias, respectively.

The beam plasma potential data was plotted relative to space plasma (V_S) potential which was defined to be zero. The stationary probe of T/S-1 was assumed to read at V_S. These assumptions have been made for this figure and subsequent plots of beam plasma potential (Figs. 5 to 8). The S/C potential was usually near V_S for negative neut bias, near -9 v for zero neut bias, and at -29 to -48 v for positive neut biases. This data agreed with the trend of the 1970 data,(4) but the magnitude of S/C voltage was somewhat shifted as shown in Fig. 9. In 1970, the S/C voltage was about 10 v lower (greater negative magnitude) for zero and positive bias, and about the same for negative bias. Major differences between test conditions of 1979 and 1979 data were, respectively, beam current 253 mA versus 85 mA, and S/C gravity gradient versus spin stabilized.

The assumption that probe 1 reads space potential may be questioned because it is immersed in a local plasma produced by efflux from the thruster. However, a review of probe 1 data showed that it read the same voltage (relative to the S/C) whether T/S-1 was off, neut 1 on only, or both main 1 and neut 1 discharges were on. This consistency held true for zero and all bias values of the neutralizers when each neutralizer bias was set at the same value. Quite possibly the charge exchange plasma of thruster 2 created a moderately high (10^9 to $10^8/cm^3$) plasma density which coupled with a small (<3 v) voltage drop to space plasma.(4) Adding to this plasma by turning on discharges from thruster 1, merely increased plasma density without changing coupling voltage to space plasma. Therefore, the authors believe it is correct to assume that probe 1 read a plasma potential that was close (<3 v) to space plasma.

Data Summary Table

Table 1 presents the results of 18 tests conducted during the first quarter of 1979. Each of the tests described in table 1 represents operation during a single ground station pass with the exception of test 13. This test includes data from two different passes. Each line of table 1 represents one sweep of beam probe 2. Generally, thruster discharge parameters were fixed for a given test and a probe sweep was made following bias command changes. T/S-1 was completely off for tests 1 to 4; neut 1

was on for tests 5 to 10; both neut 1 and main 1 were on for tests 11 to 17; and for test 18 only, T/S-2 was off with T/S-1 on.

Probe 1 values were usually constant during a sweep, but changed occasionally by 1 count (2.4 v). When probe 1 values did change, an average value was used. Probe 2 values are listed for the beam center, beam edge, and end of travel. Both beam edge readings and both end of travel readings generally read the same and only one value is listed. Other columns of table 1 list average parameters measured during a sweep. Thruster discharge parameters were not listed, but may be found in earlier sections, entitled T/S-1 and T/S-2. The S/C position values were estimated and may be in error by $\pm 5^{o}$ with a probable error of $\pm 2^{o}$.

Figures 6 and 7 give the entire beam plasma profiles of T/S-2 for six tests of table 1. The others were not plotted for brevity. Figure 6 contains data with only neut 1 on of T/S-1. Each sub figure of Figs. 6 and 7 is for a single bias of neut 2, i.e., +50, 0, -50 v. Figure 7 contains T/S-2 beam plasma profiles with both neut 1 and main 1 discharges on. Specific discussion of the data of table 1 are provided in later sections of this paper.

Cross Neutralization

The term cross neutralization refers to current neutralization of the ion beam of T/S-2 by electrons emitted from T/S-1 which is nearly 1 meter away. Figure 8 presents neutralizer emissions and the beam plasma potentials of T/S-2 for three different discharge conditions of T/S-1. T/S-2 was operated at constant values of beam current (85 mA$\pm$3). Both neutralizer biases were zero. Condition 1, T/S-1 completely off: a normal plasma potential profile was measured with a peak at 27 v. All neutralizer emission was from neut 2. Condition 2, T/S-1 neut 1 on: part of the current neutralization (8 mA) came from neut 1 and neut 2 cut back a corresponding amount. The beam plasma potential peak reduced to 21 v. Apparently the plasma from neut 1 reduced the coupling voltage needed to draw electrons into the beam. (Coupling voltage is the difference between neut cathode potential and beam center.) Condition 3, T/S-1 and neut 1 and main 1 both on: apparently the additional plasma flowing out of main 1 discharge chamber created a dense enough plasma, that beam current neutralization preferentially flowed from neut 1 (50 mA) while neut 2 cut back to 20 mA! This splitting of the neutralizer emission randomly varied $\pm$15 mA about the values given above. Presumably the emission variation was a result of neutralizer flow-control variation.

In addition to the splitting of neutralizer emission, a lower neutralizer coupling voltage resulted, and the width of the beam was reduced. The narrower beam occurred in several other tests under similar conditions and was apprently real. The total neutralizer emission for condition 3 was less than for condition 1 or 2 (which agreed within a count accuracy). Presumably, main 1 discharge ions were returning to S/C structure and the resulting excess of electrons supplied the neutralizer deficit. Net electrons may have flowed from mean 1, but they would not have read on 1-I5 telemetry which only senses net ion emission.

Figure 8 shows a sharing of current neutralization from emitters at the same potential level. It was also possible to bias one of the neutralizers and force all the emission from the other. The table below gives four cases of neut bias and the effect on emission control.

Control of Neutralizer Emission by Bias

(Bias voltage relative to S/C)

Thruster 1		Neut bias, v		Neut emiss, mA		Test no.
Neut	Main	I-V9	2-V9	1-I9	2-I9	
On	Off	+6	0	0	80	7
On	Off	+12	0	0	73	13
On	Off	0	+22	73	2	6
On	Off	0	+6	80	0	11

(Thruster 2 on at 83 mA beam.)

The first case (line 1) shows that only +6 v was needed to cut off emission from neut 1 when main 1 was off. When neut 2 was biased (line 3), it required +22 v to cut its emission back to 2 mA and force most of the emission from neut 1. Lines 2 and 4 show corresponding biases needed to force all emission from either neutralizer when main 1 discharge was on in addition. The conclusion was that sufficient coupling plasma existed between the thrusters to permit neutralization from either neutralizer with only modest (+) bias required to drive all neutralizer emission from either neutralizer. The primary source of this coupling plasma was main 1 discharge when on and the charge exchange ions of T/S-2 at other times.

A test, not listed in table 1 was performed to study any effect on cross neutralization due to change in discharge potential level in T/S-1. The discharge voltage 1-V4 was changed over its command range of 35 to 39 v, and the beam probe 2 was swept after each change. Differences in plasma potential were 1 count or less for each 1-V4 change. Differences in emission split between neutralizers were random and of the same magnitude as prior operation of zero bias on both neutralizers. The conclusion was that 4 v difference in main discharge plasma potential caused little or no change in the plasma that exits from the grids of T/S-1.

Reference 2 noted that the thrust of T/S-2 was measured while in the cross neutralization mode, and no change ($\pm$5% accuracy) was measured compared with normal neutralization. Thus, cross neutralization of T/S-2 did not cause measurable beam divergence increase. In fact, beam plasma potential data indicate a divergence decrease (narrower beam, Fig. 8) for cross neutralization. The thrust change due to the indicated divergence decrease was less (<1%) than the accuracy of thrust measurement (3%) and would not have been seen in the thrust measurement data.

Electron Current Short-Fall

For normal thruster operation the exhaust beam current and the neutralizer emission current are equal and balanced. For some of the data presented herein, the neutralizer emission was less than the beam current. This difference was called electron current short-fall. As a few mA actual current unbalance would cause large S/C potential buildup in miliiseconds (not observed), such unbalance or short-fall could not exist in reality and some

explanation must exist for the apparent short-fall data. The table below gives examples of electron current short-fall at low (-9 v) and moderate (-46 v) negative S/C voltages. Short-fall electron currents could not be measured at zero or positive S/C voltages, because increased neutralizer emission was produced which went directly to S/C ground. This fact had been previously confirmed in both ground and space tests.[4] Part of the short-fall current might have been due to net emission of electrons from the main discharge of T/S-1 when this discharge was on. Reference 3 found that 10 to 20 mA of net electrons (presumably primary electron in the discharge) may be extracted from the main discharge of a SERT II thruster operated with no high voltages. If such net emission of electrons occurred on the S/C thruster, it would not be indicated by telemetry.

Electron Current Short-Fall Table

Thruster 1		Neut bias, v		S/C voltage, v	Beam, mA 2-I5	Neut emiss, mA		Accel, mA 1-I6	Current short-fall, mA	Test no.
Neut	Main	1-V9	2-V9			1-I9	2-I9			
Off	Off	0	0	-9	85	--	80	---	4	1
On	Off	0	0	-8	83	8	67	0.0	7	7
On	On	0	0	-9	88	50	21	.8	15	13
Off	Off	---	+46	-44	85	--	73	---	11	1
On	Off	+46	+44	-46	83	8	47	0.1	27	5
On	On	+46	+44	-48	83	21	21	6.8	33	11

(2-I6 current constant, 1.1 mA, true beam current is I5-I6.)

A discussion of reasons for electron current short-fall is appropriate, not only to explain this phenomenon, but also to gain insight about the plasma surrounding the thrusters and S/C. Sources of ions that might fall back to the S/C (and hence balance the electron emission shortage) at low negative potential were: charge exchange ions from the ion beam, ions from either neutralizer discharge of the main discharge of T/S-1 after passing through the grid system, beam ions directly striking the accel grid, and ions from the ambient space environment. (Note that photo emission of electrons is not significant.[4])

In test 1 of the table above, T/S-1 was off and the probable source of fall back ions was charge exchange ions. With the S/C at -9 v, the short-fall was only 4 mA and fell within telemetry uncertainty (1 count; I5 is 5 mA, I6 is 0.1 mA, and I9 is 7 mA). The authors believe, based on a number of measurements, that the 4-mA value was real and nearly correct. When in test 1 the S/C was lowered to -44 v, more charge exchange ions were pulled back to the S/C, and the short-fall increased to 11 mA.

When neut 1 was turned on, tests 7 and 5, additional ions were added to the local S/C plasma and some were drawn back to the S/C. At -8 v the short-fall was 7 mA, a small increase over 4 mA. At -46 v S/C potential more ions were drawn back and the short-fall increased from 11 to 27 mA. At -46 v a measurable ion current, 0.1 mA, was collected by the accel grid of T/S-1. This grid was tied to S/C ground and was acting as a Langmuir probe.

When the main discharge of T/S-1 was turned on, test 13, a large source of ions and electrons was added to the local S/C plasma. This increase of plasma could have increased the ion return current or added net emission of electron current, thus increasing the short-fall to 15 mA for test 13. For test 11 at -48 v S/C potential, the short-fall increased to 33 mA. During both tests 13 and 11, ion currents of 0.8 and 6.8 mA, respectively, were drawn by accel grid 1. These accel grid current values indicated an increase in local plasma density when the main discharge was turned on.

Conclusions were that the electron current short-fall was due either to local S/C plasma ions falling back to S/C ground surfaces or to net electrons emitted from T/S-1 main discharge. In either case the currents are not measured by telemetry. As the local spacecraft plasma increased in density or the S/C potential was lowered, more ions were drawn back. For example, if the accel grid is considered as a negatively biased probe, its measured collected ion current (1-I6) was consistent with a local S/C plasma density of 10^9 to 10^{10} ions/cm^3.

Neutralizer Keeper Voltage Charge

The neutralizer keeper (anode) potential controls and is equal to the plasma potential of the neutralizer discharge. Tests were conducted to vary this plasma potential and measure any effect on the neutralizer coupling or beam plasma potential.

In test 3 the neutralizer keeper of T/S-2 was commanded to 23 v, 5 v lower than normal. Comparison of test 3 with test 1 (28 v keeper) indicated no significant effect in either neutralizer coupling or beam plasma potentials for a full range of biases on the neutralizer cathode.

Large changes in neut keeper potential were attempted in test 10. T/S-2 was operated with neut 2 bias set at +29 v to suppress neut 2 emission. Neut 1 was then turned on and probe 2 was swept as neut 1 keeper potential dropped from its starting value of 329 v to its operating value of 28 v. The first line of test 10, table 1, was taken before neut 1 ignited. The presence of neut 1 keeper at +329 v had no effect on T/S-2 or its beam plasma potential. The second line of test 10 was taken after neut 1 just lighted and the keeper was +94 v. The beam plasma potential was lowered and the S/C potential raised, both due to available electrons from neut 1. These trends were continued in lines 3 and 4 of test 10 as the neut 1 discharge became fully lighted and the keeper voltage dropped, i.e., more available emission from neut 1 caused the beam plasma potential to drop and S/C potential to be raised. The conclusion was that the presence of neut 1 keeper plasma at high voltages (+94 v) did

not noticeably effect the beam plasma potential of T/S-2. What did happen was the T/S-2 beam plasma reacted to the presence of available electrons from neut 1 and adjusted as electrons from this source became more numerous.

Interaction with Cold Gas Jets

Test 4 was conducted with the objective of measuring any interaction between the operation of cold gas jets (used for attitude control of the SERT II S/C) and an operating ion thruster. The gas jets were located on the same surface of the S/C as were the ion thrusters. The gas jets used in this experiment, nozzles 1C and 2A, exhausted their gas at right angles to the long axis of the Agena body and away from the active ion thruster. Each jet exhausted 3.3×10^{-4} kg/sec of freon-14 gas when on. Rearward free expansion of the gas from the jets was calculated to produce a gas pressure in the thruster beam of 10^{-6} to 10^{-5} torr.

During test 4, the beam probe 2 was swept three times, once with no gas jet on, and twice with gas jets on. The conclusion of test 4 was that there was no noticeable effect of the gas jet operation on either the operation of the ion thruster or on its beam plasma potential profile.

Southern Hemisphere Probe Data

Because reference 4 had shown some dependence of beam plasma potential data on S/C latitude, test 16 was performed to obtain data at southern latitudes. Test 16 may be compared with test 13 which was identical in procedure except that test 16 was taken later in the same orbit when the S/C was over Australia. For test 13 the S/C was over England where most of the probe results of this paper were obtained. The results of test 16 show no significant difference from test 13 in the beam plasma potentials nor in any thruster operating parameter. However, the S/C potential does go more negative over Ascension Island in the South Atlantic when the thruster was off. A passive S/C reacted to local space plasma variations, where as an active (thruster on) S/C reacted much less if at all.

S/A Connection

Beam plasma potential measurements (for the solar array negative side grounded to the S/C) were compared with those for the solar array center tap to S/C ground. These two S/A connections were made for tests 1 and 2 for the case of T/S-2 only operating, and for tests 13 and 17 for the case of T/S-2 and both discharges of T/S-1 operating. In each series of tests no change occurred in beam plasma potentials, in probe 1 potentials, nor in neutralizer coupling currents as the S/A voltage level was switched. The authors believe that the entire S/C, including the S/A, was immersed in a low-energy, high-density plasma resulting from thruster efflux. This plasma dominated or controlled the S/C potential level. Changes in the S/A potential within this plasma cloud merely resulted in different magnitudes of electrons or ions being drawn to the exposed S/A connector areas. The level of these magnitude changes were apparently small compared to the sensitivity of S/A current telemetry (1 count = 0.8 A).

The potential of the quiet (thrusters off) spacecraft, however, did react to the switching of the S/A grounding point. With the S/A center tapped to ground, the probe 1 voltage indicated a S/C potential of -7 v. When the S/A was switched to negative ground, the S/C potential was driven to -29 v. This was due to electrons attracted to the exposed S/A connectors at the positive end which had been increased by +30 v. The above change was the most dramatic observed and occurred while the S/C was over the South Atlantic anomaly. When the S/C was at other positions, the S/C potential was between -2 and -5 v for the S/A at center tap ground and varied from -2 to -22 v for the S/A negative grounded. The quiet S/C equilibrium potential depends on many parameters, including local space plasma and exposed S/C conducting areas. It was beyond the scope of this paper to log these changes with time and attempt to model them.

S/C Wake Effects

The SERT II spacecraft was spin stabilized such that probe 1 would alternately pass into a S/C wake or ram position. Probe 1 was located in the spin plane of the S/C and the spin plane was co-planar (within ±15°) with the orbit plane. The probe alternately sensed the potential of the S/C plasma wake and that of space plasma, approximately 20 cm in front of the S/C. The data from this probe under various test conditions is given in the table below. The probe readings were positive, corresponding to negative S/C potentials.

Probe 1 Data, Volts Relative to S/C Frame

	S/A ground		S/C position
	Negative	Center-tap	
Passive S/C	2 to 5 14 to 29	2 5 to 7	N. latitudes S. Atlantic
Active S/C (T/S-2 only) (T/S-1 + T/S-2)	 9 9	 9 9	 Any Any

The data can be interpreted as follows. For the passive S/C over England, the S/C potential was near space plasma potential. The change due to the probe passing into the wake was lost within telemetry accuracy for a center-tap grounded S/A, but showed in the data for a negative-grounded S/A. The 5 v value in line 1 above was assumed to be the actual S/C negative potential, and the 2 v reading was assumed to indicate the potential inside the S/C wake, which was expected to be more negative. For the passive S/C over the South Atlantic, the S/C potential was driven to greater negative potential by the anomalous high-energy space electron flux. With the S/C at greater negative potentials, wake effects were more distinctly seen in the telemetry data. The higher voltage in the table represented the S/C potential, and the lower voltage represented a potential within the S/C wake plasma.

For the active S/C at any position, the thruster efflux plasmas dominated or filled in the S/C plasma wake. If a difference existed in the wake plasma, it was smaller than probe telemetry accuracy (1 count = 2.7 v). Small (±1 count) differences occasionally occurred in probe 1 readings, but could not be correlated with S/C position, attitude, nor thruster parameter change. Approximately 80% of the active S/C time was at probe 1 voltage of 9 v.

Spacecraft Plasma Model

Five local spacecraft plasmas may be produced by the following ion sources of the SERT II thrusters:

- Primarily beam of T/S-2, 85 mA
- Charge exchange ions from T/S-2 beam, ~9 mA
- Neutralizer discharge, T/S-2, ~2 mA
- Neutralizer discharge, T/S-1, ~2 mA
- Main discharge, T/S-1, ~40 to ~80 mA

Electrons may be emitted from either neutralizer cathode of the T/S-1 main discharge cathode. Figure 10 represents these ion sources and possible plasma density expansion values.

The primary ion beam density was calculated from a known flux and ion velocity. The primary beam gradually diverges, until after $\sim 10^3$ meters, it has reached ambient space plasma density. References 6 and 7 indicated an ambient space plasma density of $\sim 10^4/cm^3$ for the SERT II S/C altitude of 1000 km. The properties of the charge exchange plasma of T/S-2 have been calculated by others(8,9) and were estimated to contain an ion current of about 10% of the primary beam or about 9 mA. This current corresponds to a calculated density of 10^9 to 10^{10} ions/cm^3. Each neutralizer discharge was assumed to have a local ion density of about 10^{10} /cm^3 and emit about 2 mA of ions.(10)

The plasma density downstream of a SERT II thruster operating at the same conditions as T/S-1 was measured by reference 3 in a laboratory tank.(3) The main discharge exhaust plasma was found to have an ion density of about $10^{10}/cm^3$ and an electron temperature of 3 eV at a location 15 cm downstream of the thruster grids. The ions leaving the grid system were estimated to be between 40 and 80 mA with no grid voltage. Assuming a hemispherical expansion of this plasma with an ion energy of about 1 eV (based on ground tests(4)), resulted in a density of $10^8/cm^2$ at a distance of 1 meter and a density of $\sim 10^4/cm^3$ (ambient) at approximately 25 meters.

T/S-2 only on. - Current neutralization and space neutralization were both provided by neut 2 plasma bridge. The charge exchange plasma was not important except to provide ions to the S/C to balance any electron emission shortfall. The potential between the neutralizer and beam adjusted automatically to provide the required currents. Some of these electrons may have been ambient space electrons with a balanced amount of neutralizer electrons coupled to ambient plasma by the charge exchange or neutralizer plasma.

The number of slow electrons required for space charge neutralization of the ion beam depends on the equilibrium state reached between the beam and its ambient plasma. Some attempt has been made to analyze the potential shape of the beam and the loss and gain of electrons.(8) The work has not been completed, but the electron current need is certainly less than the beam current. The net number of electrons injected into the beam need only balance those lost from the beam. Current neutralization of the ion beam, however, requires an equal number of ions and electrons be emitted. Any excess electrons over those required for space change neutralization may be emitted and travel to ambient space plasma without ever passing into the beam.(11)

T/S-1 and T/S-2 both on. - A dense plasma was created by the slow ions produced by T/S-1 main discharge. Neut 2 was no longer tightly coupled to its beam current and current neutralization could be taken over by neut 1. There were not enough probes on the SERT II S/C to determine if neut 1 electrons pass into T/S-2 beam or if they merely diffuse to ambient space to provide current neutralization. The calculated plasma density 1 meter away from T/S-1 (edge of beam 2) due to the main discharge was about $10^8/cm^3$. This density, combined with an electron temperature of 1 to 3 eV and a reasonble beam edge area (less than 1 meter length), was a sufficient source to supply all the electrons required by the ion beam. In fact, the data of this report showed that at equal bias current neutralization electrons were preferentially emitted from neut 1 and that their coupling voltage (neut cathode to ion beam center) was lower than when only neut 2 was emitting. When neut 2 was biased positively, its emission was cut off and all emission came from neut 1 or main 1. Likewise, when neut 1 was biased negatively, most or all the emission was forced from this neutralizer.

When the main 1 discharge was turned off, the plasma density dropped between T/S-1 and T/S-2. The split of neutralizer emission now favored neut 2 at equal bias. However, the charge exchange plasma from T/S-2 still produced sufficient plasma coupling, that when neut 2 was biased positive, most of its emission was cut off and neut 1 supplied the bulk of the current neutralization.

The plasma current diagram of Fig. 10 supports the observed data findings of this report, but quantative plasma measurements in the regions would be required to construct a complete plasma model. The only flight data available was from the two plasma potential probes and the neutralizer current emission and bias data. Ground data(3,10) tell us a probable plasma density and electron temperature. The flight plasma potential data can be used to indicate potential gradients in the space between T/S-1 to T/S-2. As the table below indicates, there was very little plasma potential gradient when both neutralizers were biased zero, but up to 8 v difference when neut 2 was negatively biased. The largest gradient occurred when T/S-1 was off and neut 2 was at +46 v bias. The probe voltages are listed for each probe at its end-of-travel position. Table 1 may be used if values are desired for beam edge and center.

Test	Neut 1	Main 1	1-V9	2-V9	Probe 1, v	Probe 2, v	Δv_{1-2}
1	Off	Off	0	0	9	9	0
1	Off	Off	0	+46	44	23	21
1	Off	Off	0	-44	0	-6	6
7	On	Off	0	0	8	8	0
7	↓	↓	+8	0	9	8	1
5			0	+34	17	15	2
7			-46	0	0	-2	2
9			0	-44	-1	-8	7
13	On	On	0	0	9	7	2
13	↓	↓	+12	0	12	9	3
11			0	+6	12	7	5
13			-40	0	0	-7	7
15			0	-40	0	-8	8

Multiple Thruster Neutralization

The results of the SERT II cross neutralization tests herein indicate that future multiple thruster systems should have little problem in coupling neutralizer current emission from any neutralizer for any thruster. Sufficient low-energy plasma will exist from charge exchange and neutralizer plasmas that the coupling of both space charge neutralizing electrons and current neutralizing electrons can be readily accomplished. In fact, neutralizer control may need to be addressed (depending on the way thruster grounds are made) to limit neutralizer emission and prevent possible over-emission from a single neutralizer. Such over-emission would jepordize the integrity and lifetime of that neutralizer. Interactions between neutralizer flow loops are also possible and need study.

The realization that cross neutralization was so easily accomplished on the SERT II S/C, leads to the supposition that the design of present plasma bridge neutralizers can be greatly improved in the area of electron coupling. Improvements will take the form of increased production of low-energy ions by the neutralizer discharge, perhaps even the addition of a magnetic field to improve the discharge efficiency. As much research has gone into the main discharge chamber to raise its efficiency, it seems prudent to use this technology to assist in the design of any neutralizer improvements.

A marked change of neutralizer design philosophy may be accomplished through the introduction of a concept of using only one, efficient neutralizer for an entire array of thrusters. A concept of one "super neutralizer" offers many possible advantages, such as a reduction in the number of system components, a possible increase in performance through less consumption of power and propellant, and a simplifying of neutralizer control. One of the nonoperating thrusters of a system might even serve as such a super neutralizer or as a reserve backup neutralizer.

Concluding Remakrs

The SERT II spacecraft, launched in 1970 for a 1 1/2-year mission, has been maintained in a low-key, but active status since and been used to obtain additional information on thruster system technology. This report presents one segment of this additional SERT II mission. Orbital dynamics forced this additional segment to wait until 1979 when the spacecraft achieved first continuous sunlight since 1972. Although not part of the original SERT II mission, the data obtained in these tests has provided new insight into the neutralization of ion beams in space. The data indicate that an ion beam in space need not be neutralized by a physically close electron source. Electrons may be emitted 1 meter away and be conducted by a low-energy plasma that exists between the electron source and the ion beam. The low-energy plasma may be generated by either charge exchange beam ions or by separate means, such as, the main discharge chamber of a thruster. The results of this paper, although only in a preliminary model stage, suggest that improvements in multiple thruster neutralization are possible. A single neutralizer might be used for an entire array of ion thrusters, leading to system simplicity and a reduction of power and propellant consumed in neutralization.

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TABLE 1. - SUMMARY OF SERT II BEAM PROBE DATA AND NEUTRALIZER CROSS-COUPLING TESTS CONDUCTED IN EARLY 1979

(Voltages relative to spacecraft ground)

Test 1
Pass 2

Objective: Measure T/S-2 beam plasma with various bias to neut 2. Solar array positive to spacecraft ground.

	Neut	Main
T/S-1	Off	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
Off	+50	44	84	33	23	85	Off	1.1	Off	73	Off	46	58	-4	56
	+25	29	60	24	15			1.1		80		22		4	40
	0	9	36	13	9			1.1		80		0		6	33
	-25	0	22	-2	-2			1.2		130		-24		3	43
	-50	0	8	-10	-6			1.2		231		-44		0	50

Test 2
Pass 70

Objective: Measure spacecraft potential and beam plasma with solar array center-tapped (60 v total).

	Neut	Main
T/S-1	Off	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
Off	+50	43	87	35	22	83	Off	1.1	Off	73	Off	46	±30	3	43
	+25	29	60	25	15					77		22		4	40
	0	9	38	13	9					80		0		8	26
	-25	0	29	-2	-5					140		-22		6	33
	-50	1	26	-12	-9			1.2		230		-44		0	50

Test 3
Pass 10

Objective: Change neutralizer keeper voltage and measure effect on beam plasma and spacecraft voltages (2-V8 is 23 v, 5 v lower).

	Neut	Main
T/S-1	Off	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
Off	+50	43	84	33	21	83	Off	1.1	Off	60	Off	44	58	-80	28
	+25	29	60	24	13	83		1.1		67		22		-82	34
	0	8	38	14	9	85		1.1		80		0		-76	14
	-25	0	24	-2	-2	85		1.2		148		-22		-83	38
	-50	0	14	-12	-6	85		1.3		230		-44		-78	21

Test 4
Pass 281

Objective: Measure interaction between plume of cold gas jets and ion thruster.

	Neut	Main
T/S-1	Off	Off
T/S-2	On	On

Command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
Gas jets	Bias 2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
Off	0	9	38	15	7	85	Off	1.1	Off	80	Off	0	58	6	33
On	0	10	36	15	7	88	Off	1.0	Off	86	Off	0	58	4	40
On	0	9	36	15	7	88	Off	1.0	Off	83	Off	0	58	1	46

Test 5
Pass 77

Objective: Measure neutralizer coupling.
Bias neut 1: various.
Bias neut 2: constant, +50 v.

	Neut	Main
T/S-1	On	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
+50	+50	46	82	35	22	83	0.1	1.1	8	47	46	44	58	153	-44
+25		38	63	33	19		.1	1.0	41	21	22	44		156	-51
0		17	53	26	15		0	1.1	73	0	0	34		162	-60
-25		0	22	10	4		0	1.0	124	0	-24	14		157	-54
-50		0	14	5	0		0	1.1	195	0	-46	-4		159	-57
0	0	8	Off	Off	Off	83	0.0	1.1	13	59	0	0	58	151	-37

TABLE 1. - Continued.

Test 6 Objective: Measure neutralizer coupling.
Pass 76B Bias neut 1: various.
Bias neut 2: constant, +25 v.

	Neut	Main
T/S-1	On	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	+25	31	58	25	15	83	0.1	1.1	8	73	28	22	58	-150	61
+25	+25	29	53	25	15	↓	.1	↓	15	60	22	22	↓	-147	64
0	+25	14	41	20	10	↓	0	↓	73	2	0	22	↓	-133	73
-25	+25	0	22	12	10	↓	0	↓	124	0	-24	6	↓	-144	68
-50	+25	0	9	2	-2	↓	0	↓	189	0	-46	4	↓	-138	71
0	0	9	Off	Off	Off	83	0	1.1	13	56	0	0	58	-153	58

Test 7 Objective: Measure neutralizer coupling.
Pass 76A Bias neut 1: various.
Bias neut 2: constant, zero.

	Neut	Main
T/S-1	On	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	0	9	37	12	8	83	0.1	1.1	0	80	8	0	58	-156	52
+25	↓	9	34	12	8	↓	.1	↓	0	80	6	↓	↓	-158	48
0	↓	8	29	12	8	↓	0	↓	8	67	0	↓	↓	-147	64
-25	↓	0	14	8	4	↓	0	↓	117	8	-24	↓	↓	-153	58
-50	↓	0	9	5	-2	↓	0	↓	195	0	-46	↓	↓	-150	61

Test 8 Objective: Measure neutralizer coupling.
Pass 76/76A Bias neut 1: various.
Bias neut 2: constant, -25 v.

	Neut	Main
T/S-1	On	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	-25	0	29	-4	-3	83	0	1.1	0	150	-6	-24	58	-125	76
+25	↓	↓	33	-4	-3	↓	↓	↓	0	150	-6	↓	↓	-133	73
0	↓	↓	26	-4	-6	↓	↓	↓	0	143	0	↓	↓	-4	56
-25	↓	↓	21	-6	-5	↓	↓	↓	86	130	-26	↓	↓	-77	81
-50	↓	↓	14	-11	-6	↓	↓	↓	189	104	-48	-26	↓	-114	78

Test 9 Objective: Measure neutralizer coupling.
Pass 77A Bias neut-1: various.
Bias neut 2: constant, -50 v.

	Neut	Main
T/S-1	On	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	-50	-1	31	-12	-8	83	0	1.2	0	234	-6	-46	-58	-147	64
+25	-50	-1	38	-12	↓	85	↓	↓	0	230	-6	-44	↓	-144	68
0	↓	-1	22	-10	↓	85	↓	↓	0	228	0	-44	↓	-114	78
-25	↓	-2	29	-12	↓	85	↓	↓	41	230	-26	-46	↓	-133	73
-50	↓	-2	22	-14	↓	83	↓	↓	138	182	-47	-45	↓	-125	76

Test 10 Objective: Measure neutralizer-1 coupling as it is lighting.
Pass 65 Bias neut 1: constant, zero; 1-V8, various values.
Bias neut 2: constant, zero; 2-V8, constant, 28 v.

	Neut	Main
T/S-1	On	Off
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V8, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
0	+25	29	58	30	16	83	0	1.1	0	80	329	22	-58	-11	8
↓	↓	20	46	25	15	↓	↓	↓	41	41	94	↓	↓	-14	-5
↓	↓	17	41	23	13	↓	↓	↓	60	15	36	↓	↓	-15	-9
↓	↓	17	36	23	13	↓	↓	↓	67	8	29	↓	↓	-16	-15
↓	↓	9	26	10	7	↓	↓	↓	28	47	28	0	↓	-18	-22

TABLE 1. - Continued.

Test 11
Pass 123

Objective: Measure neutralizer coupling.
Bias neut 1: various.
Bias neut 2: constant, +50 v.

	Neut	Main
T/S-1	On	On
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	+50	48	60	36	19	83	6.8	1.1	21	21	46	44	56	0	50
+25	↓	34	41	23	14	88	5.6	↓	40	2	24	26	58	-2	53
0	↓	12	17	12	7	83	1.5	↓	80	0	0	6	58	5	36
-25	↓	0	2	-1	-5	83	0	↓	177	0	-25	-6	56	3	43
-50	↓	0	7	0	-10	83	0	↓	282	0	-41	-6	58	1	46

Test 12
Pass 105

Objective: Measure neutralizer coupling.
Bias neut 1: various.
Bias neut 2: constant, +25 v.

	Neut	Main
T/S-1	On	On
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	+25	33	50	26	17	88	5.9	1.1	0	52	34	22	58	1	46
+25	↓	31	43	24	14	↓	5.6	↓	41	18	22	22	↓	-2	53
0	↓	12	17	12	7	↓	1.2	↓	80	0	0	6	↓	6	33
0	↓	9	17	12	7	↓	1.6	↓	73	↓	0	0	↓	-6	59
-25	↓	0	2	-2	-5	↓	0	↓	176	↓	-24	-6	↓	-8	63
-50	↓	0	7	-4	-7	↓	0	↓	280	↓	-40	-6	↓	3	43
0	0	Off	Off	Off	Off	88	0.6	1.1	60	15	0	0	58	-20	72

Test 13
Pass 106/915

Objective: Measure neutralizer coupling.
Bias neut 1: various.
Bias neut 2: constant, zero.

	Neut	Main
T/S-1	On	On
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	0	12	36	15	9	88	2.6	1.1	0	73	12	0	58	3	43
+25	↓	12	33	15	9	↓	2.4	↓	0	73	12	↓	58	-2	53
+25	↓	12	36	17	9	↓	2.2	↓	0	67	12	↓	61	3	43
0	↓	9	22	9	7	↓	.8	↓	50	21	0	↓	58	7	30
0	↓	9	19	10	7	↓	.6	↓	54	8	0	↓	61	5	36
-25	↓	0	7	0	-3	↓	0	↓	169	0	-24	↓	61	1	46
-25	↓	0	7	1	-2	↓	0	↓	176	0	-24	↓	58	6	33
-50	↓	0	9	-5	-7	↓	0	↓	280	0	-40	↓	58	5	36

Test 14
Pass 104

Objective: Measure neutralizer coupling.
Bias neut 1: various.
Bias neut 2: constant, -25 v.

	Neut	Main
T/S-1	On	On
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longitude	Latitude
+50	-25	0	19	0	-3	88	0	1.1	0	156	-4	-25	58	0	50
+25	↓	↓	22	-1	-3	↓	↓	1.1	0	156	-6	↓	↓	-2	53
0	↓	↓	24	1	-3	↓	↓	1.2	0	156	0	↓	↓	5	36
-25	↓	↓	9	-3	-5	↓	↓	1.1	169	107	-25	↓	↓	3	43
-50	↓	↓	7	-9	-8	↓	↓	1.2	273	46	-41	↓	↓	1	46
0	0	Off	Off	Off	Off	88	0.6	1.1	65	8	0	0	58	-6	59

TABLE 1. - Concluded.

Test 15
Pass 102

Objective: Measure neutralizer coupling.
Bias neut 1: various.
Bias neut 2: constant, -50 v.

	Neut	Main
T/S-1	On	On
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
+50	-50	0	41	0	-8	88	0.2	1.3	0	273	-6	-42	56	-87	48
+25	↓	↓	50	0	-8	88	.1	1.3	0	267	-6	-42	56	-88	51
0			43	0	-8	88	.1	1.3	0	273	0	-40	58	-82	34
-25			24	-7	-8	85	0	1.2	150	254	-24	-44	56	-83	38
-50			17	-12	-12	85	0	1.3	273	215	-42	-44	56	-84	41
0	0	9	Off	Off	Off	88	0.7	1.1	67	15	0	0	58	-90	54
0	0	9	Off	Off	Off	88	.5	1.0	47	28	0	0	58	-92	58

Test 16
Pass 106A

Objective: Repeat test 13 in southern hemisphere.
Bias neut 1: various.
Bias neut 2: constant, zero.

	Neut	Main
T/S-1	On	On
T/S-2	On	On

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
+50	0	12	34	15	10	88	2.4	1.1	0	73	14	0	56	149	-34
+25	↓	12	31	15	10	↓	1.8	↓	0	73	16	↓	58	147	-24
0		9	22	10	7		1.0		41	34	0		58	154	-47
-25		0	7	0	-5		0		176	0	-24		58	153	-43
-50		0	9	-3	-7		0		280	0	-40		56	151	-37
0	0	9	Off	Off	Off	88	1.3	1.1	52	15	0	0	58	145	-17

Test 17
Pass 114

Objective: Repeat test 13 with solar array switched to center tap (58 v total).

	Neut	Main
T/S-1	On	On
T/S-2	On	On

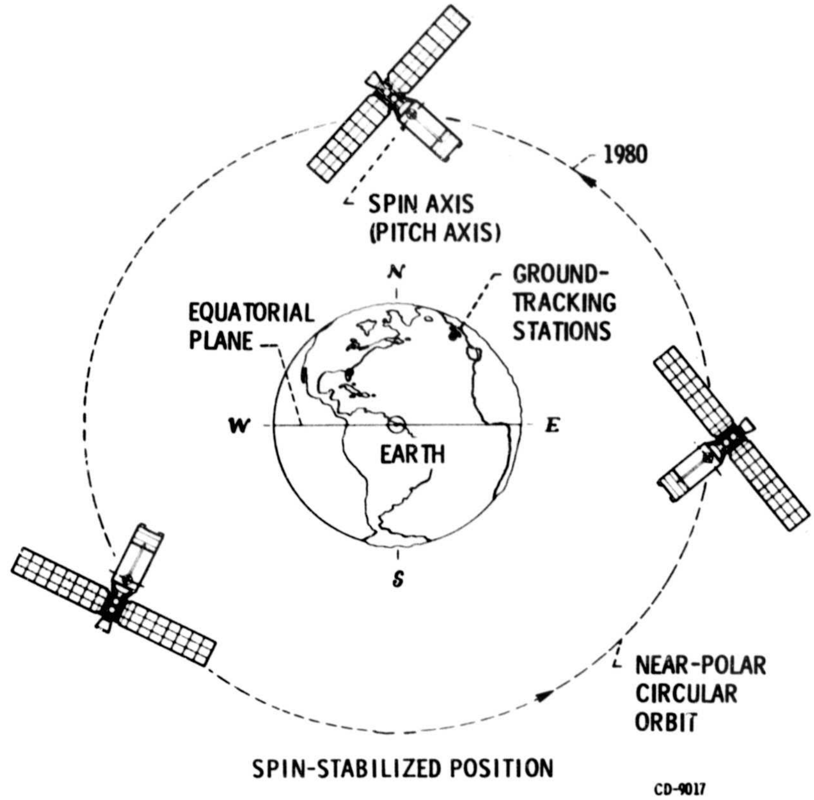
Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
+50	0	12	36	17	10	83	2.3	1.1	0	73	13	0	±29	0	50
+25	↓	13	31	17	10	85	2.6	↓	0	73	14	↓	↓	-4	56
0		9	17	13	7	↓	1.0		41	28	0			6	33
-25		0	7	1	-5		0		177	0	-24			4	40
-50		0	9	-3	-8		0		280	0	-38			3	44
0	0	9	Off	Off	Off	88	0.7	1.1	34	34	0	0	±29	-8	63
0	+50	12	Off	Off	Off	88	1.3	1.1	73	0	0	6	±29	-15	69

Test 18
Pass 12

Objective: Control spacecraft potential with thruster-1 only. (No ion beam on.)

	Neut	Main
T/S-1	On	On
T/S-2	Off	Off

Bias command		Probe voltage from S/C, v				2-I5, mA	1-I6, mA	2-I6, mA	1-I9, mA	2-I9, mA	1-V9, v	2-V9, v	$V_{S/A}$, v	S/C position	
1	2	Probe 1	Beam center	Beam edge	End-2									Longi-tude	Lati-tude
+50	Off	0	0	0	0	Off	0	Off	0	Off	-6	Off	60	-2	53
+25	↓	0	0	0	0	↓	↓	↓	0	↓	-4	↓	61	-6	59
0		4	2	2	2				0		0		60	6	30
-25		0	-2	-2	-2				143		-22		60	4	40
-50		1	-5	-5	-10				273		-44		60	1	46



VEHICLE COORDINATE SYSTEM IN ORBIT VIEWED FROM SUN

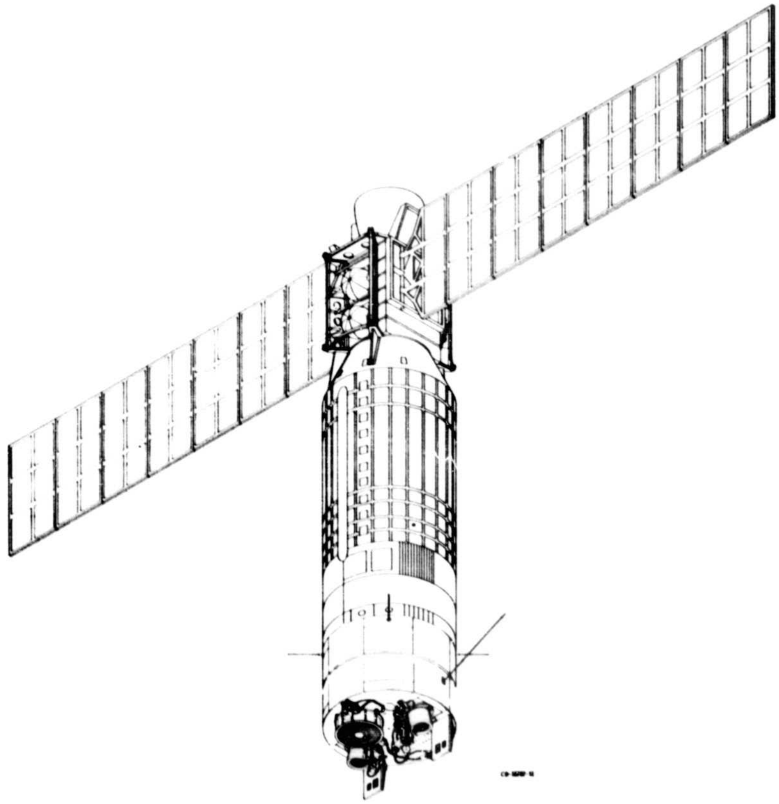


Figure 1. - SERT II spacecraft in orbit (artist's conception).

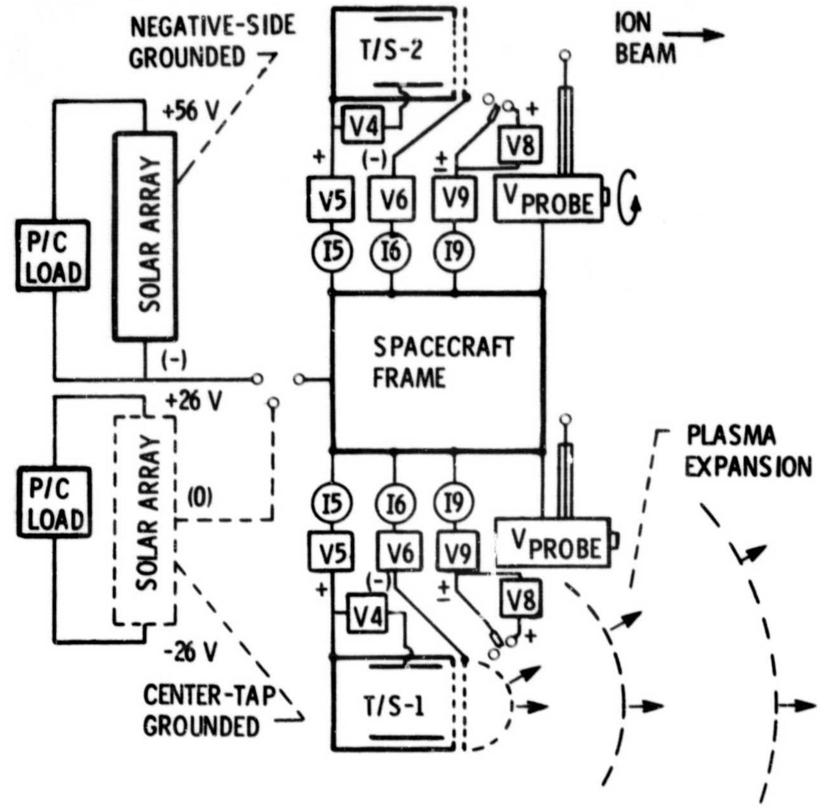


Figure 2. - SERT II power supply and solar array circuits.

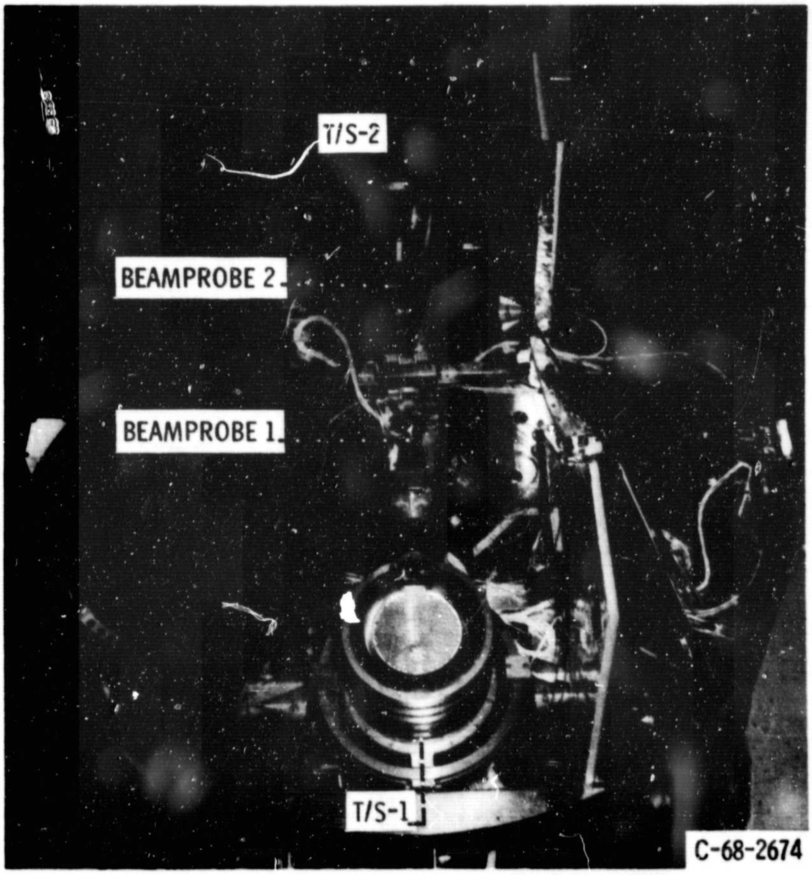


Figure 3. - SERT II spacecraft showing thrusters and beamprobes.

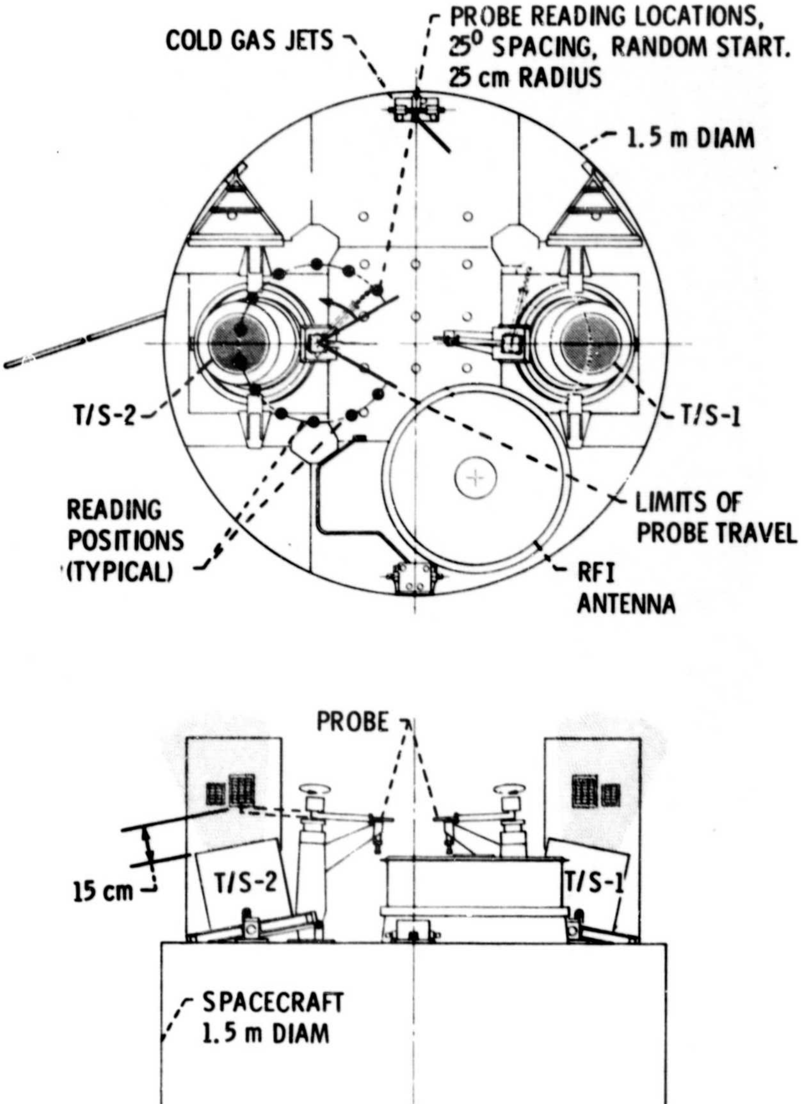


Figure 4. - SERT II spacecraft drawing showing beam probe location.

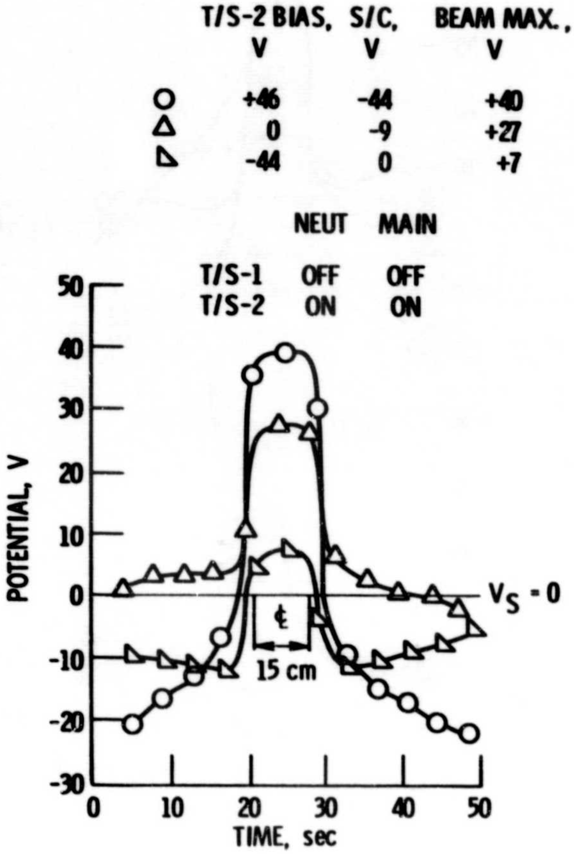


Figure 5. - Beam plasma potential of thruster 2 with various neutralizer bias voltages (test 1, table I). Thru Thruster 1 is off. Abscissa is typical for all probe sweep plots; probe updates every 4 seconds; first update at 2±2 seconds.

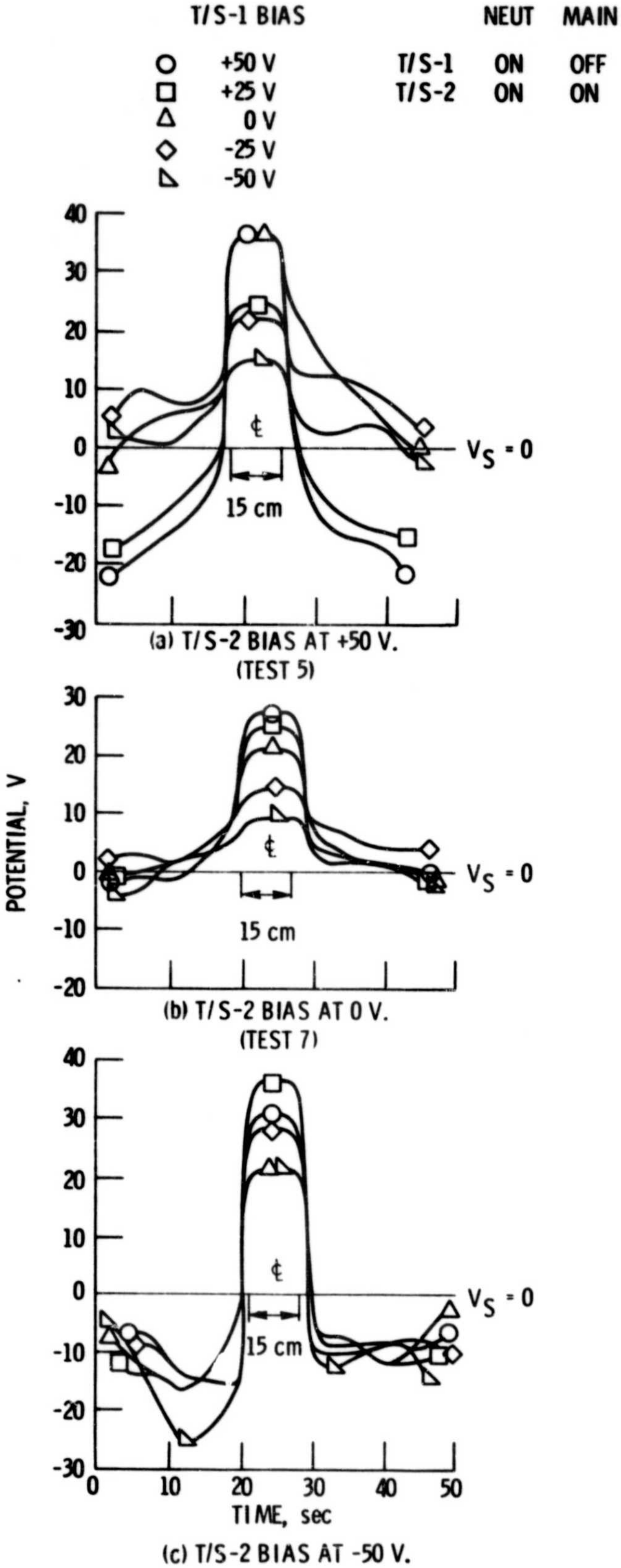


Figure 6. - Beam plasma potentials for various tests with neutralizer-1 on.

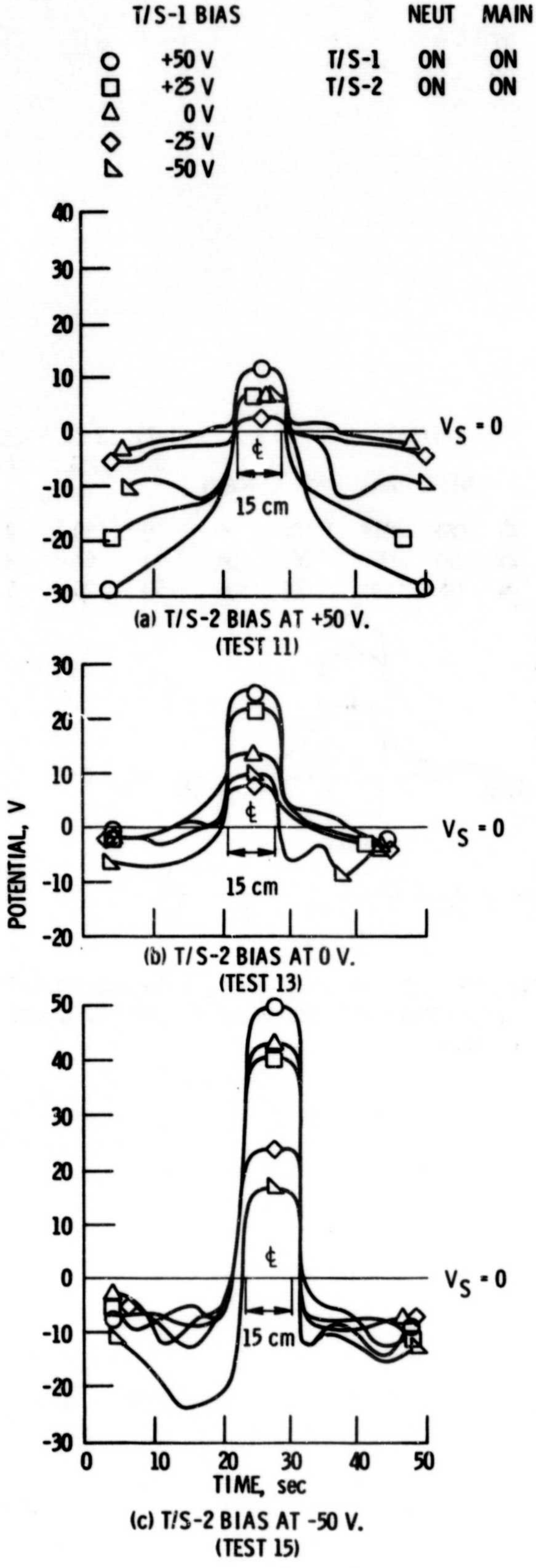


Figure 7. - Beam plasma potentials for various tests with both neut-1 and main-1 discharges on.

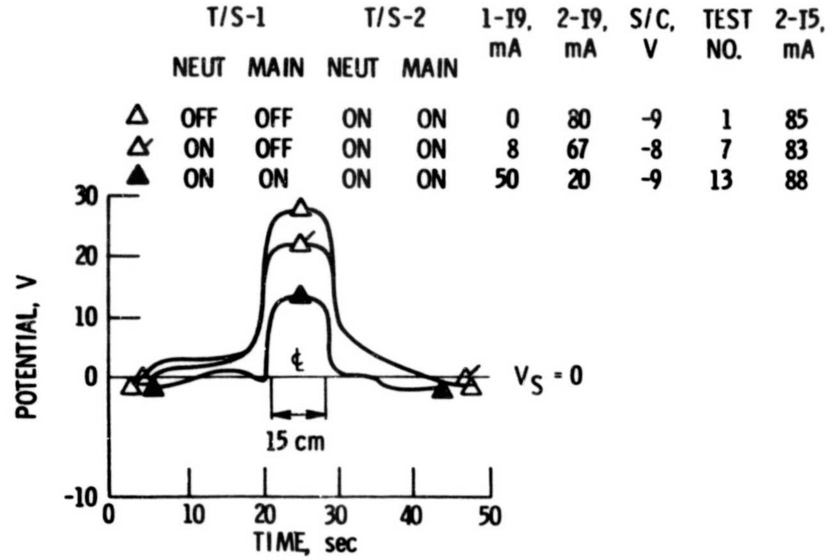


Figure 8. - Comparison of beam plasma potential of thruster 2 with various thruster 1 discharges on. Zero bias, both thruster neutralizers.

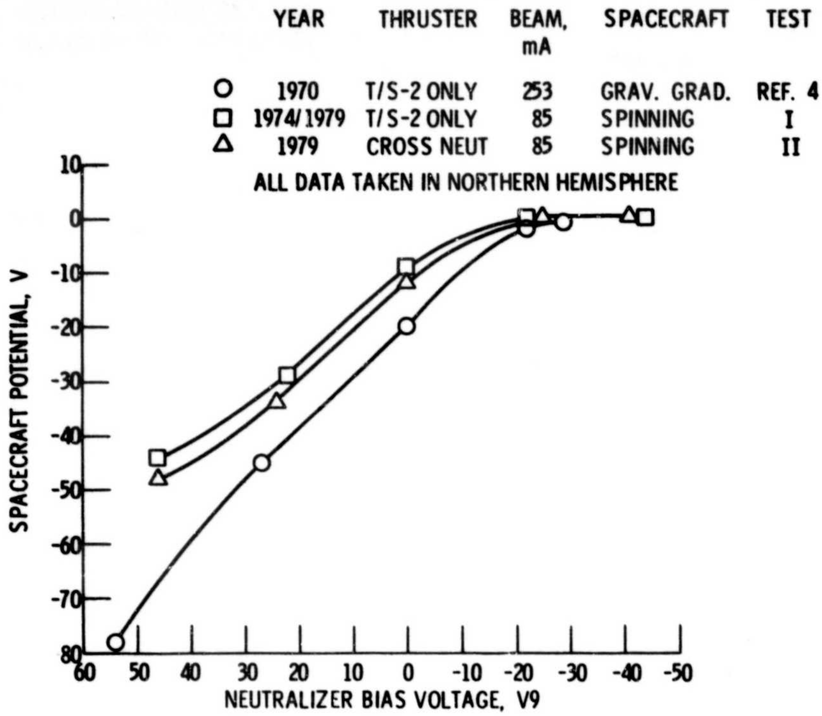


Figure 9. - Spacecraft potential as a function of neutralizer bias voltage.

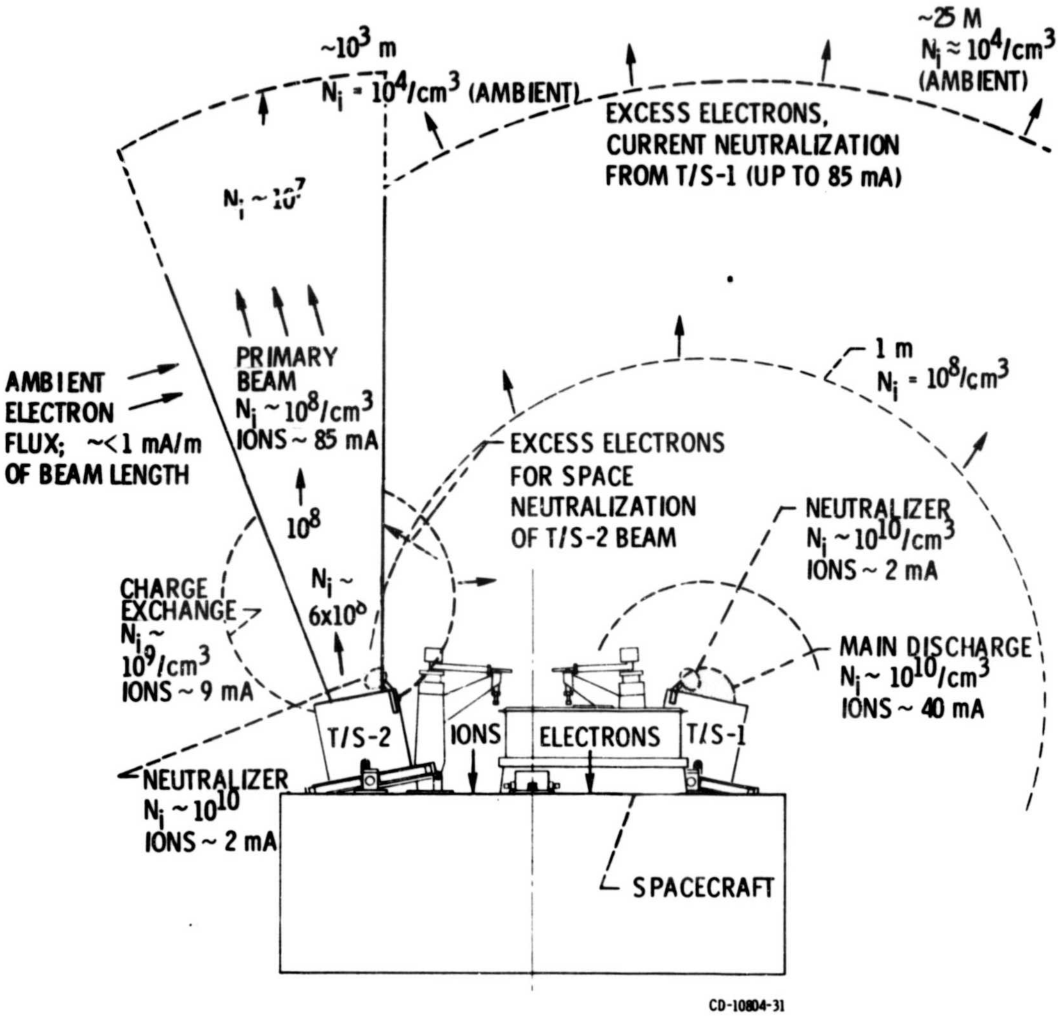


Figure 10. - Spacecraft plasma current diagram.